Feasibility of using Electrodynamic Wheels as a Suspension, Propulsion, and Guidance method for a Hyperloop pod

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Abstract:

The Hyperloop is a mass transportation concept. Its defining feature is that a high speed pod travels within an evacuated tube to reduce drag. This can in part be done by levitating the pod above the tube it travels in. There are two distinct methods to accomplish this: air ejected from the bottom of the pod to generate lift or an electromagnetic levitation system, such as used in maglev trains. One such electromagnetic levitation system makes use of electrodynamic wheels, a halbach array looped along the outside of a wheel. As the wheels move relative to the track, the magnetic flux induces currents in an electrically conductive track below it. These currents produce a magnetic force that interacts with those produced by the wheels attached to the pod. This interaction suspends the pod above the track, and can also provide lateral stability and thrust to propel the pod. This paper details the decisions on the number, size, placement, and other specifics of the wheels to be used in a half-scale prototype pod being built by the Hyperloop Team at the University of Virginia.

Keywords: Hyperloop, Electrodynamic Wheels, Maglev, Electromagnetic Suspension

Introduction

In 2012 Elon Musk, the founder and CEO of SpaceX and Tesla, mentioned his idea for a high speed mass transportation concept, which he named the “Hyperloop”. The concept is defined as a capsule that moves through an evacuated tube. In many proposed designs, the pod levitates above the bottom of the tube to reduce drag. In 2015, SpaceX organized a competition for university student teams to flush out the idea and build a prototype. Many of the teams decided to drastically change the design. The element of design most commonly changed was the pod’s suspension system. Originally, Musk proposed using “air skis”: air ejected from the bottom of the pod to keep it off the tube. However, many of the teams instead chose to design a suspension system utilizing electromagnetic effects. One possible levitation design uses “electrodynamic wheels” (EDWs): wheels with magnets along the circumference in a specific orientation. The wheels move relative to an aluminum track below it, generating a magnetic flux that induces currents in the track, which in turn generates a field that opposes the wheels, causing the wheels to levitate. To improve performance, the wheels were optimized to have the highest ratio of lifting force to weight. The Hyperloop Team at the University of Virginia will use this design in a prototype that will be raced at the Hyperloop Pod Competition II, which is hosted by SpaceX.

Advantages and Disadvantages of EDWs

Generally, electromagnetic suspension systems have a higher initial implementation cost compared to another suspension system such as air skis. However, air skis use pumps and other elements with higher maintenance costs.

When comparing EDWs to other electromagnetic systems, there are quite a few advantages. The first is that the electrodynamics wheels can be used as normal physical wheels, which makes transporting the pod much easier, and also safer if lift is lost. Additionally, the EDWs can be driven like normal wheels to get the pod moving. Driving these wheels can only provide thrust for the pod up to a certain speed, however, another advantage of the EDWs is that they can generate a thrust force if they have a positive slip. Correspondingly, if the wheels have a negative slip, a drag force is produced, which can be useful when stopping the pod. These thrust and drag forces are not as large as the lift force, so thus should be considered a bonus effect instead the main reason to use them. In addition to the thrust and lift forces, in some cases the wheels can generate a lateral guiding force, keeping the pod on track.

The main disadvantage of EDWs compared to something such as a linear Halbach array is that EDWs require motors to spin them, and the motors require batteries. Both of those are significant extra weight.

Track Design

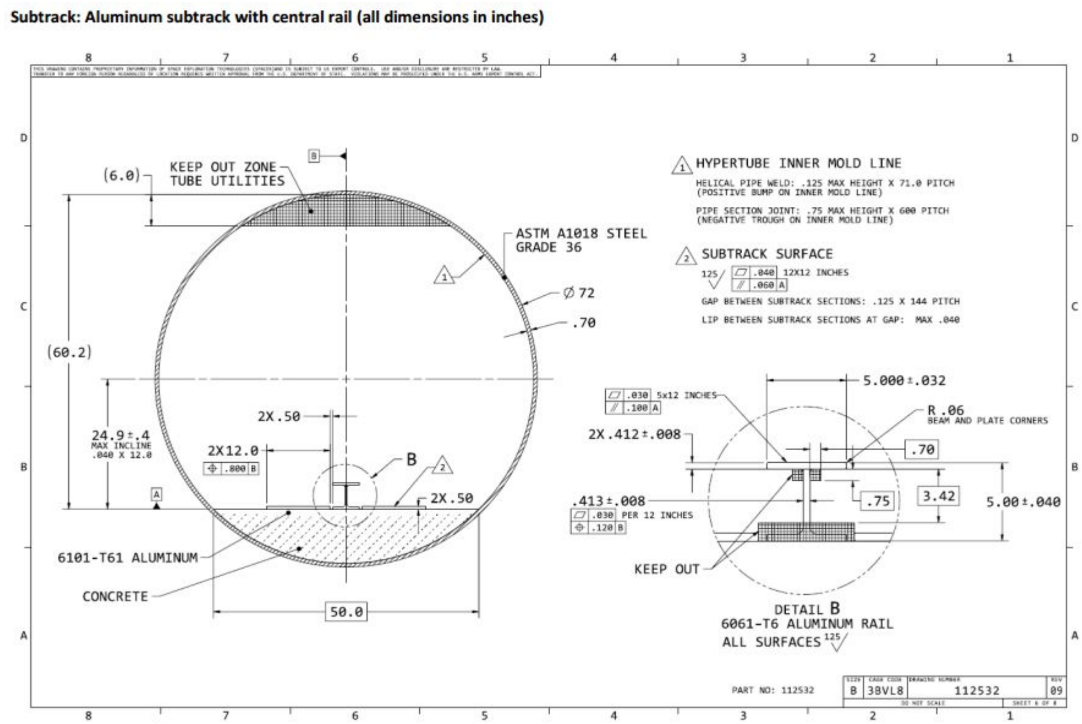
The use of electrodynamic wheels for levitation relies on having an electrically conductive track below them. The more electrically conductive, the larger the induced currents will be, which results in larger lifting forces. Theoretically, superconducting material would then be best, but for a practical and realizable track that spans hundreds to thousands of miles, as would be the case in a hyperloop track, one has to find a balance between conductivity and cost. As of November 2016, the economical choice is aluminum.

Aluminum is also what SpaceX is using in the track they are building for the Hyperloop Pod Competition II. Their track (Figure 1) has two flat aluminum plates on either side of a central I-beam. The central I-beam is made of 6061-T6 Aluminum alloy, which has a resistivity of $4\text{x}10^{-8}$ Ω*m [6]. The I-beam is not the main surface used to generate lift, but is important for guidance of the pod. The plates, which are the primary surfaces used to generate lift, are made of the aluminum alloy 6101-T61, an alloy noted for its high electrical conductivity. 6101-T61 is about 56% as conductive as copper, having a resistivity of $3\text{x}10^{-8}$ Ω*m [7].

Additionally, the SpaceX track has a small gap between the central aluminum I-beam and the flat aluminum plates. As found in Bird's paper [3] on using electrodynamic wheels with split tracks,

having the wheels centered above such a gap produces a lateral guidance force. Without this or another method to keep the pod in line with the track, the pod is unstable and will almost inevitably veer off to the side and collide with either the I-beam or the tube.

Figure 1: The test track for the Hyperloop Pod Competition II hosted by SpaceX [5].



However, there are some restrictions in using this gap. The first is that the area directly above the gap is labeled a restricted zone in the schematic, meaning physical parts such as the wheels cannot occupy that space.

Forces Generated by an Electrodynamic Wheel

The forces produced by the wheels were found by integrating Maxwell's stress tensors over a flat surface in the air-gap between the rotor and the guideway. The guideway field was computed using Biot-Savart's Law.

Stress tensor equations [1]:

Thrust Force: $$Fx = \frac{1}{\mu_0}\iint ByBx\,dxdz$$

Lift Force: $$Fy = \frac{1}{2\mu_0}\iint (By^2 - Bx^2 - Bz^2)\,dxdz$$

Guidance Force: $$Fz = \frac{1}{\mu_0}\iint ByBz\,dxdz$$

The opposing magnetic force induced in the track comes from Faraday's Law of induction: $\nabla \times \widehat{E} = -\frac{\delta \widehat{B}}{\delta t}$, where ∇x**E** is the curl of the electric field, and **B** is the magnetic flux. This demonstrates that the amount of "curling" in the electric field is proportional to the rate that the magnetic flux is changing through a section of the track over time. In other words, a changing magnetic field induces currents in the track. These currents then create a magnetic field opposing the one generated by the wheels, producing lift. The lift force can thus be increased by increasing the rate of change of magnetic flux through the track. The most obvious way of doing this is by increasing the relative speed of the wheels.

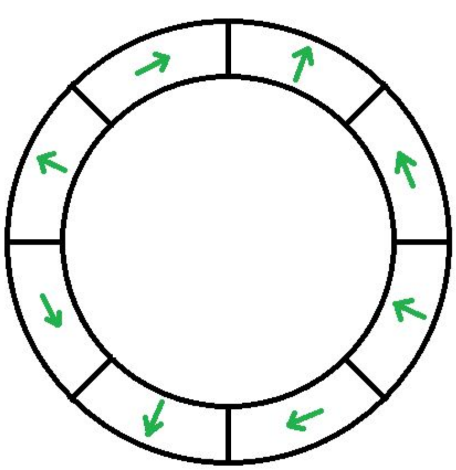
Wheel and Track Clearance

Although there are other methods of laterally stabilizing the pod, it was decided that the design should take advantage of the passive guiding forces generated by having EDWs over the gap between the bottom of the I-beam and flat plate. This requires wheels that have a maximum diameter of 3.42" and levitate a minimum of 0.756" above the bottom of the I-beam. This gap was rounded to 2 cm in the design to give a clearance of 1 mm. The wheel diameters were also reduced. The resulting wheels were not big enough to lift the pod effectively, so it was decided to have separate wheels further away from the I-beam. The gap between these and the flat aluminum plates was chosen to be 1 cm.

Magnet Orientation and Number

An electrodynamic wheel is defined as a circular Halbach array. This means the magnets are placed such that the fields follow the arrows in the diagram below. Previous research [2] indicated a Halbach array with 4 pole pairs has the highest lift to weight ratio.

Figure 2: Halbach array with 4 pole pairs. The green lines indicate the direction of the magnetic field.



Number of Wheels
To evenly distribute weight and stress within the structure supporting the wheels, and to take advantage of the effect of wheels in series, it was decided to place two lifting wheels next to each other in a pair, with two of these pairs on the left and right side near the front of the pod and two similarly positioned on the back for a total of 8 lifting wheels. There is a motor for each pair of wheels. The motor drives the two lifting wheels by connecting their axles to the motor's rotor with splines. There are also 8 guidance wheels, 4 on each side. Two wheels are as forward as possible on the pod, two and as far back as possible, and the other four are evenly spaced from those in the midsection. The guidance wheels are driven with a smaller separate motor each.

Wheel Size
It was found in previous research [2] that the highest lift to weight ratio occurred in a wheel with the magnets along the circumference with an outer diameter of 28 cm. It was also found in the same paper that the optimal lift to weight ratio occurred when the length of the inner diameter was 81% of the outer, making the optimal inner diameter ~25 cm. This indicates a magnet thickness of 2.5 cm, which is approximately 1 in. For the guidance wheels to fit within the constraints imposed by the I-beam and no go zones, the maximum diameter was restricted to 3.42". To provide clearance, the guidance wheels were chosen to have an outer diameter of 8 cm, with the thickness of the magnets found to 8 mm, which was derived using the same optimal ratio of inner to outer radius as the lifting wheels.

To find the required magnet thickness to lift our pod with an approximate weight of 2,500 N, we first found a relation between lift and width, which was:

Lift = (number wheels) * (lift force generated by each wheel per unit width) * (width of single wheel)
2,500 N = 8 * 5,000 N/m * (width of single wheel)
(width of single wheel) ~= 0.052 m ~= 2 in.

Where the lift force generated by each wheel per unit width was extrapolated from the lift forces found in [2]. In that paper, a lift force per unit thickness of ~30,000 N/m was found by simulation. It is important to note that this simulation took place at a lower traveling velocity, and without taking into account the effects of the wheels being in series. The setup in the aforementioned simulation had the same air gap between the wheels and the track, but differed in other parameters. A correction factor of 0.14/0.23 was applied to take into account the different radii, another factor of 2.5/3.5 for the higher conductivity of the track used in that paper, and 0.5/0.4 to for the different track thicknesses. Other factors were discounted as negligible, but if accounted for, they would've been in our favor for a reduced thickness. With all the correction

factors applied, the resultant conservative estimate of lift per unit width is 20,000 N/m, which means a required magnet width of 1.6 cm ~= 0.63 in.

Since the planned thickness of the magnets was ~1 in, and it is convenient to buy and assemble a halbach array with the correct pole orientation using cubes than it is bars, the magnet thickness was chosen to also be 1 in, a good amount above the minimal estimate of 0.63 in. This provides a factor of safety should the pod end up weighing more than expected.

Similarly, for the guidance wheels, it was more convenient to work with cubicle magnets, and so a thickness of 2x 8 mm thick magnets was chosen to adequately straddle to split rail to utilize guidance forces.

Effect of Wheels in Series

One method of achieving larger lift forces is to use a number of Halbach EDWs in series. If a second EDW is rotating closely behind the first, the induced currents in the track from the first wheel produce a magnetic force on the other wheels as well, and vice-versa. Thus, the second wheel will be able to use some of the currents induced in the track by the first EDW, so the second EDW will not have to expend as much energy in order to create the same forces as the first. [4]

With two wheels in series, a local maxima in the generated lift to wheel weight ratio occurs with a slip speed of only 2 m/s [2]. The next local maxima of L/W occurs at a slip of about 43 m/s, and in general the Lift to Weight ratio increases with the slip speed, the speed of the wheels relative to the track. Theoretically, it would then be desirable to spin the wheels as fast as possible. Practically however, a higher slip speed necessitates faster motors that draw more power, and the increasing weight of these motors and the batteries necessary to power them outpaces the gains from running them at a higher speed. Thus 2 m/s is chosen to be the slip velocity.

Cost Analysis

Each of the 28 cm diameter wheels would require 24 1 in x 1 in x 1 in cubicle magnets to make. With 8 of those wheels, that is 192 of those magnets at $5.65 each [8], making the total cost of the lifting wheel magnets ~$1,100 with shipping. The 4 guidance wheels use 48 magnets each at a cost of $1.16 per magnet [9]. This makes the total cost of the lifting guidance magnets ~$250 with shipping. The larger motors that drive the lifting wheels cost about $70, and those driving the guidance wheels cost $15 for a total cost of motors of ~$400. This is a subtotal of $1,900 with a few hundred dollars likely to be used in the aluminum casing that holds the magnets, batteries, and rubber to use the EDWs as normal wheels, bringing the approximate cost to $2,000.

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